

## NUMERICAL INVESTIGATION ON THE PERFORMANCE OF A ROCKFALL DRAPERY SYSTEM

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**Abstract.** This paper presents a discrete modelling approach which allows the simulation of rockfalls behind drapery systems. The falling rock is represented by a rigid assembly of spheres whereas the slope is represented by triangular elements. Energy dissipation during impact on the slope is considered via friction and viscous damping. The drapery is represented by a set of spherical particles which interact remotely. The numerical model is used to investigate the efficiency of a drapery system. Various simulations with two different block sizes are performed and the numerical predictions of simulations with drapery are compared to simulations without drapery in order to assess the performance of the protection system.

### 1 INTRODUCTION

The rockfall hazard in areas such as mountainous regions, quarries and mines needs to be rigorously managed in order to avoid fatalities, damage to infrastructure and production losses. It is almost impossible to prevent rockfall events but the installation of rockfall protective systems, such as draperies, is a common and effective way to mitigate the hazard. Simple drapery systems consist of flexible wire meshes draped over the rock surface [1]. The drapery covers the extent of the initiation zone of rockfall prone areas

but rocks can still detach and fall in between the mesh and the rock face. The purpose of the drapery is to cover the slope and to control the path of rocks and debris [2].

Numerical tools are usually used to optimise the design of protective systems and to assess the residual hazard involved with such systems. Although several numerical models for restraining nets and net barriers have been presented in the literature (see e.g. [3]), the modelling of draperies as a whole system has been addressed only recently. Most of the models are based on the finite element method (FEM). A study using shell finite elements was presented in [4] whereas the authors of [5] and [6] used truss finite elements to model the drapery. A more advanced drapery model using a special purpose finite element code was presented in [7]. The discrete element method (DEM) was used to model rockfall meshes, where the mesh is discretised by spherical particles, in references [8, 9, 10] and recently it has also been applied to model rockfalls with drapery systems [11].

The study presented in this paper focuses on the discrete modelling of a simple drapery system presented in [11], implemented in the open-source framework YADE [12, 13]. The falling rock is represented by a rigid assembly of spheres whereas the slope is represented by triangular elements. Energy dissipation during impact on the slope is considered via friction and viscous damping. The drapery is represented by a set of spherical particles which interact remotely (i.e. interactions between the particles exist without direct contact) as in [14]. The numerical model is used to investigate the efficiency of a drapery system. Various simulations with two different block sizes are performed and the numerical predictions of simulations with drapery are compared to simulations without drapery in order to assess the performance of the protection system.

## 2 NUMERICAL REPRESENTATION AND INTERACTION MODELS

The simulation of rockfalls with drapery system involves all possible interactions between the block, the slope and the drapery. In the following, the numerical representation and the interaction models of each component are discussed.

### 2.1 Block–slope interaction model

The block is modelled by a rigid assembly of uniform spherical particles (Figure 1) whereas the slope is represented by fixed triangular elements. Hence, the interaction between the block and the slope consists of the interactions of spheres with triangles. Contact forces in the normal direction are calculated using a linear–elastic spring model and the spring is only active in compression. A viscous damping element is added to the spring model in order to account for energy dissipation during the impact. The normal contact force  $F_n$  is calculated as

$$F_n = k_n u_n + \alpha \frac{du_n}{dt} \quad (1)$$

where  $k_n$  is the normal contact stiffness,  $u_n$  is the relative normal displacement,  $\alpha$  is the viscous damping coefficient and  $\frac{du_n}{dt}$  is the relative normal velocity. The damping

coefficient  $\alpha$  is directly related to the normal coefficient of restitution  $e_n$  and is given by the following relation [11]

$$\alpha = 2\sqrt{k_n m} \frac{-\ln e_n}{\sqrt{\pi^2 + \ln^2 e_n}} \quad (2)$$

where  $m$  corresponds to the mass of the spherical particle which is in contact with the triangular element of the slope. Contact forces in the tangential direction are calculated using a Coulomb-like slip model. The tangential contact force  $F_t$  is defined as

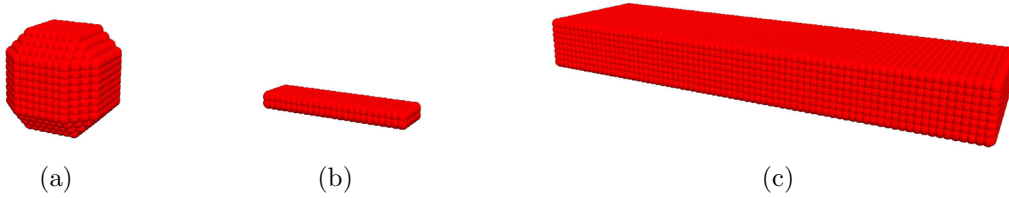
$$F_t = k_t \Delta u_t \quad (3)$$

where  $k_t$  denotes the tangential contact stiffness and  $\Delta u_t$  the incremental tangential displacement. The magnitude of  $F_t$  is limited by

$$|F_t| \leq |F_n| \tan \varphi \quad (4)$$

where  $\varphi$  corresponds to the internal friction angle. Figure 2(a) shows the rheological model for the block–slope interactions.

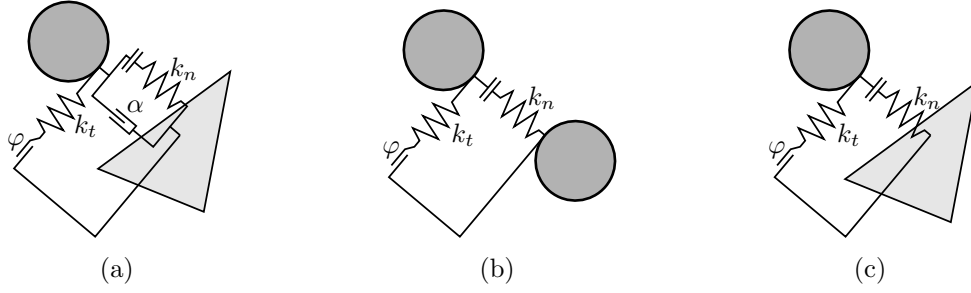
It should be noted that a realistic representation of the slope is essential for a realistic rockfall simulation. The triangulated surface model of the rock slope used in this study was derived from a high resolution geo-referenced point cloud obtained from a photogrammetric survey [15]. The various material layers were identified and corresponding values for  $e_n$  were assigned to each layer.



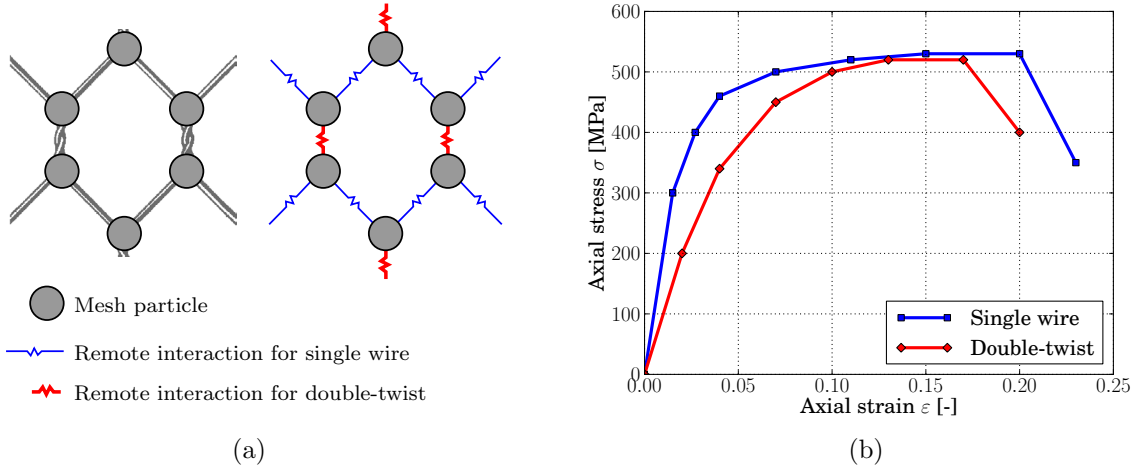
**Figure 1:** Representation of the block: (a) block used for calibration and validation and blocks used in the performance analysis (b)  $D_{90}$  and (c)  $D_{100}$ .

## 2.2 Drapery model

The drapery considered in this study consists of a double-twisted hexagonal wire mesh. In the numerical model the mesh is represented by a set of spherical particles located at its physical nodes (Figure 3(a)). A remote interaction model, where particle interact with no physical contact, is introduced in order to account for the wires between the nodes [14]. The interaction forces are defined via the stress–strain relation of the single wire and double-twist (Figure 3(b)). The model considers tensile forces only and interactions are allowed to fail. Global mesh characteristics, such as distortion of the wires and hexagons, are considered by introducing a stochastically distorted contact model. A detailed description of this model and the parameters involved can be found in [10].



**Figure 2:** Rheological model and corresponding parameters: (a) for block–slope interaction, (b) for block–drapery interaction and (c) slope–drapery interaction.



**Figure 3:** Model for the double-twisted hexagonal wire mesh (after [10]): (a) location of particles and remote interactions and (b) stress–strain relations used for single wires and double-twists.

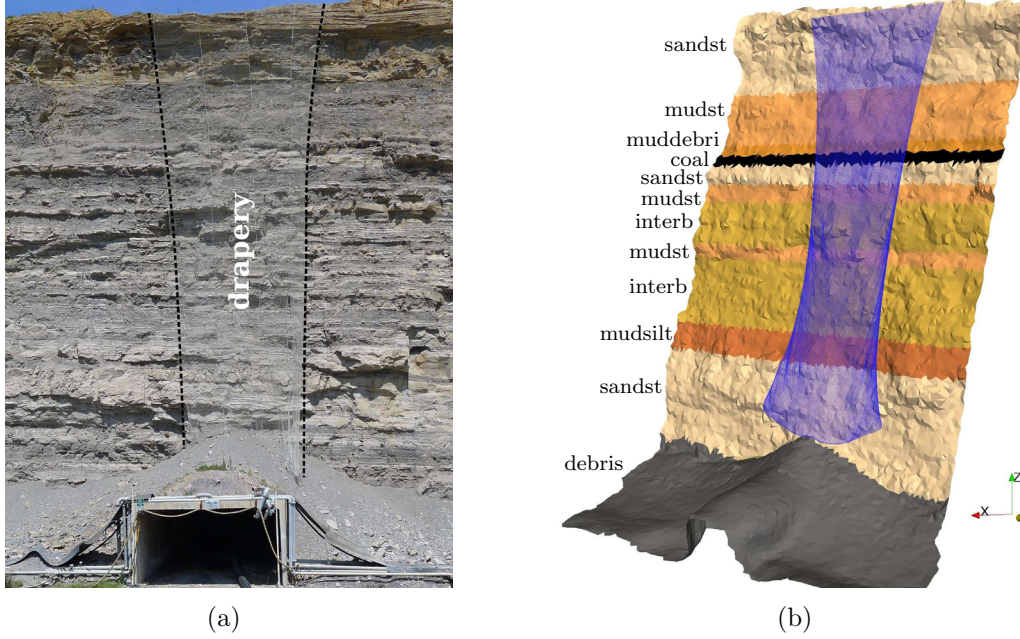
### 2.3 Block–drapery and slope–drapery interaction model

The drapery is represented by spherical particles as described in the previous section. Hence, the interaction between the block and the drapery consists of the interactions of spheres with other spheres, while the interactions between the slope and the drapery comprise interactions of fixed triangular elements with spheres. Both interactions are modelled using a linear–elastic spring model without viscous damping in the normal direction (i.e. Eq. (1) with  $\alpha = 0$ ) and a Coulomb-like slip model in the tangential direction (i.e. Eq. (3)). The corresponding rheological models are shown in Figures 2(b)–(c).

### 3 Model calibration and validation

Figure 4(a) shows a picture of the rock slope considered in this study. The slope is about 40 m high, has a dip of about 70–75° and is partly covered with a drapery. Figure 4(b) shows the numerical representation of the same slope with the material layers and the

drapery in its final equilibrium condition after it was positioned on the slope by applying gravity [11]. It should be noted that the drapery is only fixed at the top and is otherwise free to move.

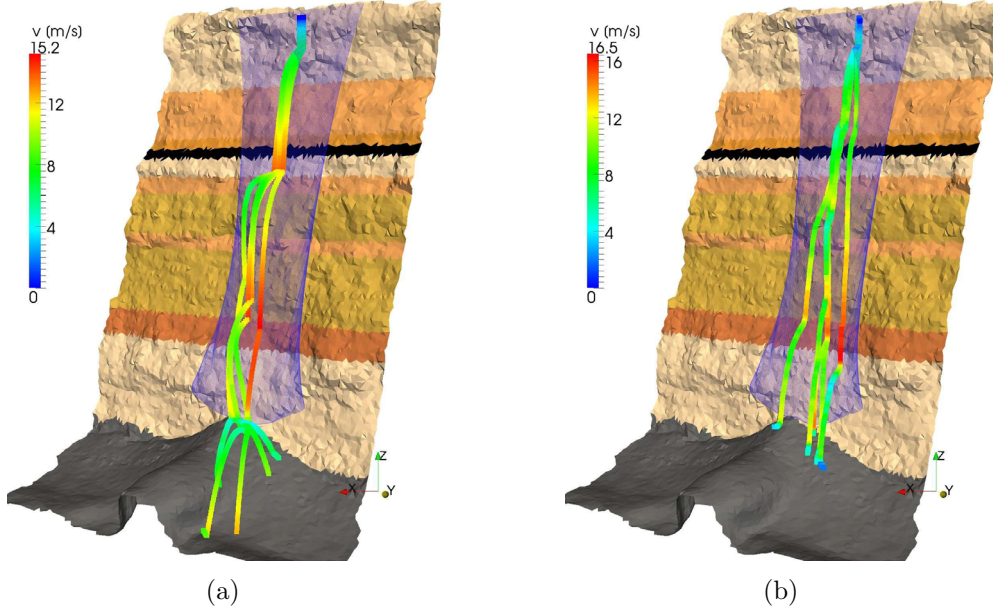


**Figure 4:** Drapery model: (a) picture of the rock slope considered in this study and (b) numerical representation.

Experimental tests presented in [16] are used to calibrate and validate the numerical model. Detailed results can be found in [17] and [11] where experimental results without drapery were used to calibrate the block–slope interaction and experimental results with drapery were used to calibrate the block–drapery interaction. The latter are summarised in Figure 5, where Figure 5(a) shows the numerical predictions by the numerical model and Figure 5(b) shows the results from the experiments. The figures show the trajectories and the corresponding absolute translational velocities along the trajectories. It can be seen that both trajectories and velocities are very similar. Therefore, it can be assumed that the numerical model gives good predictions for rockfalls with drapery systems.

#### 4 Performance of the drapery

The numerical model presented in the previous sections is used to study the performance of the installed drapery. The study is carried out by introducing two representative blocks. The slope considered in this study was part of the rockfall hazard study presented in [18], where discrete fracture network analyses were combined with kinematic analyses in order to identify shape and size distributions of unstable blocks. Results of the study indicated that 90% of the unstable blocks had a volume of  $V_{90} = 0.004 \text{ m}^3$



**Figure 5:** Trajectories and absolute translational velocity  $v$  for slope with drapery: (a) numerical predictions and (b) experimental results after [16].

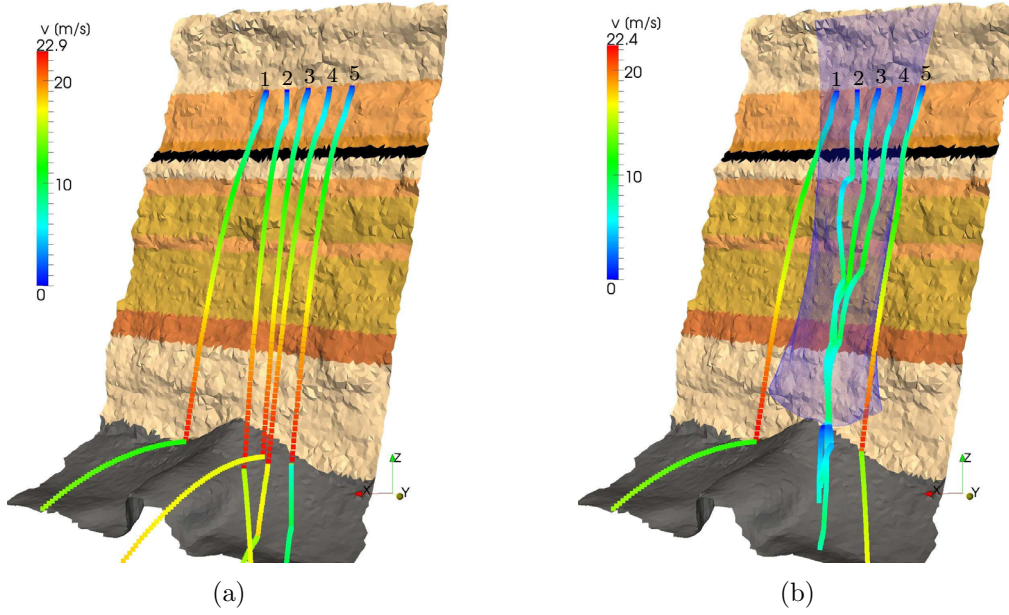
and that the maximum volume of an unstable block was  $V_{\max} = 0.115 \text{ m}^3$ . In [19] it was shown that the majority of the unstable blocks can be categorised as elongated and elongated/platy. This is taken into consideration in order to generate two blocks:  $D_{90}$  (Figure 1(b),  $0.06 \times 0.14 \times 0.5 \text{ m}^3$ ) and  $D_{100}$  (Figure 1(c),  $0.18 \times 0.42 \times 1.52 \text{ m}^3$ ).

The performance of the drapery is assessed by using both blocks and carrying out a series of five simulations for each block where the initial position of the block is varied horizontally along the slope. Position 3 is located in the middle of the drapery. All blocks are released separately. Simulations without and with drapery are carried out and compared in order to assess the efficiency of the installed system.

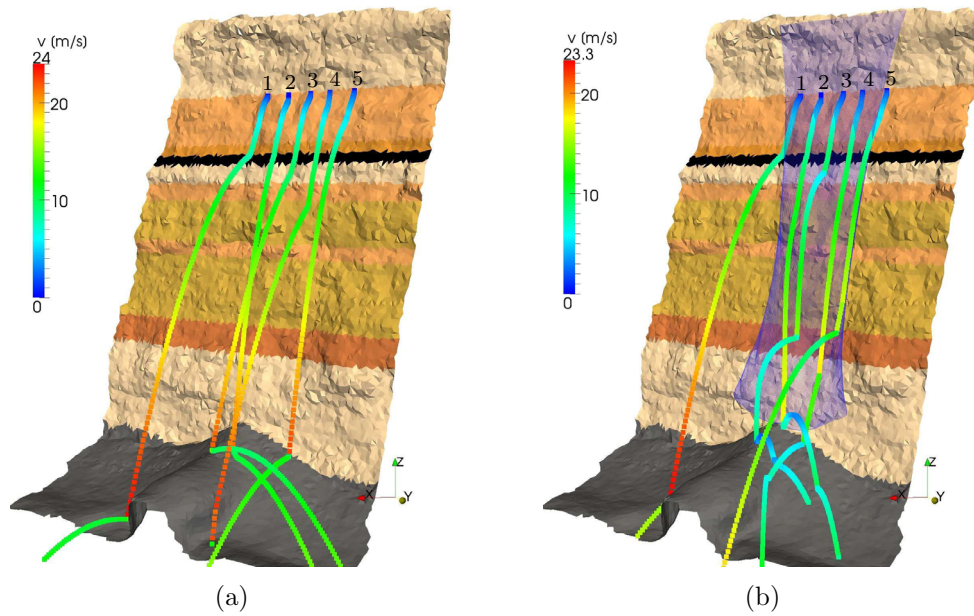
The predicted trajectories and absolute translational velocities are shown in Figure 6 and Figure 7 for block  $D_{90}$  and  $D_{100}$  respectively. When comparing Figure 6(a) with Figure 6(b) it can be seen, that the drapery has no influence on the blocks released from position 1 and 5. In both cases the block slips sidewise through the drapery in the first half of its travel. Nevertheless, the drapery is very efficient in reducing the velocity and the bouncing height for the blocks released from position 2 to 4. Similar observations are made for block  $D_{100}$  when comparing Figure 7(a) to Figure 7(b).

Figure 8 summarises the main results of the analyses. The diagrams indicate the reduction due to the drapery for the absolute translational velocity  $v$  and the horizontal distance from the wall  $d$  at the base of the slope where the drapery ends. As indicated in the previous paragraph, it can clearly be seen that the drapery is not effective for blocks released from position 1 and 5. For position 2 to 4, the drapery drastically decreases the bouncing height and horizontal distance  $d$  for both blocks and keeps the blocks close to



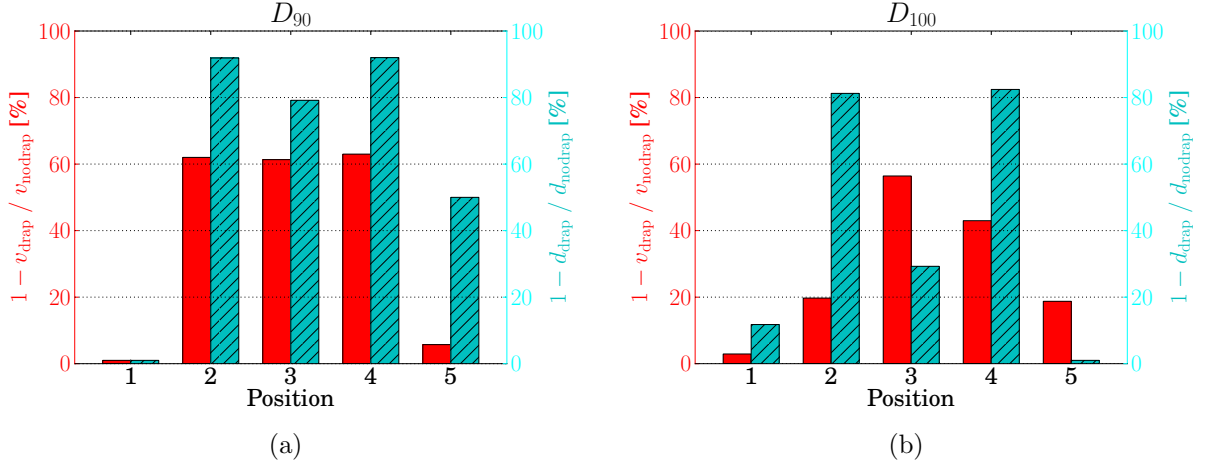


**Figure 6:** Numerical predictions for block  $D_{90}$ : (a) without drapery and (b) with drapery.



**Figure 7:** Numerical predictions for block  $D_{100}$ : (a) without drapery and (b) with drapery.

the slope. The model predicts a reduction of the bouncing height of almost 80% for all simulations except position 3 of block  $D_{100}$ . In terms of velocity reduction performance, it can be seen that the drapery is more efficient for the small block  $D_{90}$ . In this case the velocity is reduced by about 60% for blocks released from position 2 to 4. This is not the case for block  $D_{100}$  where the reduction is between 20 and 50% only.



**Figure 8:** Performance of the drapery: (a) for block  $D_{90}$  and (b) for block  $D_{100}$ .

## 5 CONCLUSIONS

This paper investigates the performance of a rockfall drapery system. The numerical model is based on the classical DEM with spherical particles. The block was modelled using a rigid assembly of spheres and the slope was represented by triangular elements. A normal linear-elastic spring model with a viscous damping element was used to model the rebound behaviour. The drapery system was represented by spherical particles and remote interactions.

A numerical study was carried out by simulating rockfalls with two different blocks and releasing them from various positions. The numerical predictions for the simulations with drapery were compared to those without drapery in order to assess the efficiency of the drapery. The results show that the drapery is very efficient in reducing the bouncing height of the block. The translational velocity is also reduced by the drapery but the system is more efficient for smaller blocks. Blocks detaching very close to the drapery's lateral boundaries cannot be restrained.

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